Observational Test of Environmental Effects on The Local Group Dwarf Spheroidal Galaxies

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ABSTRACT

In this paper, we examine whether tidal forces exerted by the Galaxy or M31 have an influence on the Local Group dwarf spheroidal galaxies (dSphs) which are their companions. We focus on the surface brightness profiles of the dSphs, especially their core radii because it is suggested based on the numerical simulations that tidal disturbance can make core radii extended. We examine the correlation for the dSphs between the distances from their parent galaxy (the Galaxy or M31) and the compactnesses of their surface brightness profiles by using a parameter "C" defined newly in this paper. Consequently, we find no significant correlation. We make some remarks on the origin of this result by considering three possible scenarios; tidal picture, dark matter picture, and heterogeneity of the group of dSphs, each of which has been often discussed to understand fundamental properties and formation processes of dSphs.

Subject headings: galaxies: elliptical and lenticular, cD— galaxies: evolution— galaxies: fundamental parameters—

1. Introduction

Recent observations have been revealing the physical properties of the Local Group dwarf spheroidal galaxies (dSphs). The dSphs have luminosities of order 10^5–$10^7\,L_\odot$, and are characterized by their low surface brightnesses (Gallagher & Wyse 1994 for review).

The observations of such low-luminosity objects are important for several reasons. One of them is that we can examine the environmental effects in detail by the observational data because such objects with small binding energies may be easily affected by their environments. For the Local Group dSphs, the tidal forces exerted by the Galaxy or M31 are likely to be the most important environmental effects. In fact, for example, Kroupa (1997) and Klessen & Kroupa (1998) theoretically discussed the fate of dwarf satellite galaxies based on the tidal effects, and Bellazzini et al. (1996) presented an observational support by examining correlations between surface brightness and tidal force (but see Hirashita, Kamaya & Takeuchi 1999).

If the tidal forces really have major effects on the dSphs, a dwarf galaxy closer to a giant galaxy (in the Local Group, the galaxy or M31) should be more disturbed and have a more extended surface brightness profile. In this paper, we independently examine this point from the observational point of view by introducing a "compactness parameter" derived from the core radius of the surface brightness profile (§3.1). Since the new data of the companions of M31 have recently been available (e.g., Armandroff et al. 1998; Caldwell 1999; Grebel & Guhathakurta 1999; Hopp et al. 1999), we use these dSphs as well as those surrounding the Galaxy.

This paper is organized as follows. First of all, in the next section, we present the sample and data. Then, we introduce the "compactness parameter" and present the result of our analysis in §3. In §4, the dark matter problem for the dSphs is discussed based on the result in §3. Finally, we summarize the content of this paper in §5.

2. Sample and Data

The physical parameters (V band absolute magnitude, core radius, and galactocentric distance from the parent galaxy) of the Local Group dSphs in Mateo (1998) are used, except for And V, VI, VII. We refer to Caldwell (1999) for these three dSphs. The adopted quantities are presented in Table 1. The galacticentric distances for the companions of our galaxy are derived from their heliocentric distances (Mateo 1998 and references therein). For the companions of M31, we calculate the distances from M31 by using both their projected and heliocentric distances, taking into account the distance from M31 to us (770 kpc; Mateo 1998), and these are presented in the column of R_{GC}.

3. Results

3.1. Definition of compactness parameter C

The physical parameters (luminosity, radius, and velocity dispersion) of the dwarf elliptical galaxies (dEs) and dSphs as well as normal elliptical galaxies are known to correlate (e.g., Peterson & Caldwell 1993). Since the dSph sample shows a more significant scatter in the correlation than the other ellipticals (Caldwell et al. 1992), we examine whether the scatter is caused by the environmental effect from the parent galaxies. For this purpose, we define the "compactness parameter" by utilizing the relation between core radius (r_c) and V band absolute magnitude (M_V). We present the data plotted on the $\log M_V - \log r_c$ plane in Figure 1. The locus of dwarf elliptical galaxies in Peterson & Caldwell (1993) is also shown by the dotted square marked with dEs. In the following, we present the definition of the "compactness parameter".

First of all, we determine the standard core radius ($r_{c,0}$) for each dSph from the

following relation,

$$\log r_{c,0} = aM_V + b. \tag{1}$$

Peterson & Caldwell (1993) analyzed 17 dEs and found that there is the scaling relation between their effective radii (R_e) and V band luminosities (L_V) as

$$L_V \propto R_e^{5.0\pm0.5}. \tag{2}$$

Here, we use this scaling relation to obtain the constant "a" in the equation (1). Although we use core radii unlike Peterson & Caldwell (1993) (they used effective radii), this has little effect on the following result since there is only a small difference between core radii and effective radii (e.g., Caldwell 1999).

Assuming that

$$L_V \propto r_{c,0}^{5.0}, \tag{3}$$

we obtain the following relation between $r_{c,0}$ and M_V:

$$\log r_{c,0} = -0.080M_V + 1.42. \tag{4}$$

We adopt the zero point "b" so that the averaged values of $\log r_c$ and M_V for our sample galaxies ($<\log r_c> = 2.34$, $<M_V> = -11.6$) satisfy the above equation, though the way to determine the zero point does not matter to the following analysis. Note that we use $r_{c,0}$ to indicate a core radius obtained for each dSph by substituting the observed M_V of the galaxy into the above mean relation. Finally, we define the "compactness parameter" (C) as

$$C \equiv \log(r_c/r_{c,0}), \tag{5}$$

where the values of r_c are listed in Table 1. Here, we comment on an error of C (referred to ΔC hereafter), which is determined from an error of r_c. Since errors of r_c are presented

in Mateo (1998), we find that almost all the absolute values of ΔC are smaller than 0.1 as given in the column of C in Table 1. It should be noted that most of the errors of $\log R_{\rm GC}$ are smaller than 0.1 as seen in Table 1. These errors are small enough to make our following discussions valid. If r_c is larger than $r_{c,0}$, in other words, $C > 0$ for a dSph, we should consider that the galaxy is more extended than it should be for its luminosity. In the context of the environmental effect, we could find a negative correlation for the sample dSphs between C and $R_{\rm GC}$ since a dSph closer to a giant galaxy should be more disturbed and more extended by the tidal effects.

3.2. Result

We present the data of our sample dSphs plotted on the $\log R_{\rm GC} - C$ plane in Figure 2. There, the Galaxy's companions are indicated by filled squares, and M31's by open squares. The correlation coefficient between $\log R_{\rm GC}$ and C with all the data is -0.28. Dividing our sample into the Galaxy's companions and the M31's ones, the coefficients become -0.36 and $+0.12$, respectively. That is, we find no significant correlation. Note that this conclusion is not altered even if a different inclination of the $\log r_{\rm c,0} - M_V$ relation (a in eq.1) is adopted within a reasonable range. Although a mean value of C for the M31 companions may be smaller than that for the Galaxy's, this difference is not significant considering a large scatter of C. For the Galaxy's companions, Sculpter could be seen as an exception and if it is removed from them, there might be the correlation (the correlation coefficient could be -0.66). This may suggest that the group of so-called dSph satellites is heterogeneous, as discussed in §4.2.

4. Discussion

4.1. The dark matter problem

To date, stellar velocity dispersions of dSphs have been extensively measured (e.g., Mateo et al. 1993 and references therein), which, in general, indicate too large mass to be accounted for by the visible stars in the dSphs. In other words, dSphs have generally high mass-to-light ratios. This fact may imply the presence of dark matter (DM) in these systems (e.g., Mateo et al. 1993). Existence of DM is supported by the large spatial distribution of stars to their outer regions (Faber & Lin 1983) and the relation between the physical quantities of the dSphs (Hirashita et al. 1999, but see Bellazzini et al. 1996). Moreover, on the basis of this DM picture, the relation between the ratio of the virial mass to the V-band luminosity and the virial mass (the $M_{\rm vir}/L - M_{\rm vir}$ relation) for the Local Group dSphs is naturally understood as the sequence of their star formation histories in their forming phases by quasistatic collapse in the DM halo (Hirashita et al. 1998).

However, the above arguments may be challenged if we consider the tidal force exerted by the Galaxy. If a dwarf galaxy orbiting a giant galaxy (the Galaxy or M31 in the Local Group) is significantly perturbed by the tides of the giant galaxy, the observed velocity dispersion of the dwarf galaxy can be larger than the gravitationally equilibrium dispersion (Kuhn & Miller 1989; Kroupa 1997). This tidal picture of the dSphs also suggests that the large velocity dispersions do not necessarily show the existence of DM. Indeed, Klenya et al. (1998) demonstrated that Ursa Minor has a statistically significant asymmetry in the stellar distribution which can be attributed to tidal effects.

In summary, about the large stellar velocity dispersions and the large $M_{\rm vir}/L$ of the dSphs, two major models are possible; the tidal heating without DM and the presence and dominance of DM. Although we cannot give a clear answer as to which of these models has more validity, we discuss this problem taking into consideration the result obtained in §3.2.

4.2. Remarks based on our result

4.2.1. Tidal picture

From the absence of the correlation between C and $\log R_{\rm GC}$ as shown in §3.2, it is not suggested that the tidal forces have major effects on the dSphs, irrespective of whether the resonant orbital coupling (Kuhn & Miller 1989) could occur or not. However, we emphasize that once the sample is split into the well-studied Galactic satellites on the one hand, and the satellites of M31 on the other hand, then the values and behaviour of C with $R_{\rm GC}$ are consistent with the tidal forces being important, at least for the companions of the Galaxy. It is noted that an orbit of a satellite may not be circular. If the orbits of the dSphs are elliptical, their present $R_{\rm GC}$'s might not reflect their averaged $R_{\rm GC}$ from past to present and $R_{\rm GC}$ may not a good measure of tidal effects unless $R_{\rm GC}$ is very small or very large. On the other hand, a satellite can pass near the parent galaxy frequently enough to allow serious tidal perturbation within a Hubble time even if the semi-major axis is 100 kpc. Thus, the correlation should disappear and the tidal picture might not be rejected completely from our result. However, if we consider a dSph in the elliptical orbit around a giant galaxy and is observed at a location relatively far from the giant galaxy, the dSph could not experience the galactic tide unless the orbit is highly elliptical. In this case, since the duration staying around the apogalacticon should be much longer (§VI of Searle & Zinn 1973), the galaxy would not suffer the tidal effect from the giant galaxy enough to be disturbed. Moreover, it should be noted that $R_{\rm GC}$s in our sample widely spread from ~ 20 to ~ 300 kpc. If $R_{\rm GC}$ is ~ 300 kpc, the orbital period is expected to be comparable to a Hubble time by assuming the Keplerian motion, which is adopted because orbits of the dSphs are still unknown in detail. Consequently, though some difficulties may exist, a dwarf galaxy closer to a giant galaxy (in the Local Group, the Galaxy or M31) should be more disturbed, and thus, it is likely that the correlation appears. That the sample of M31 companions shows a smaller

correlation than the Galactic sample may be due to the fact that the three-dimensional distance estimates M31-satellites are very uncertain, and therefore that projection can hide the tidal signature for the sample of M31 satellites.

4.2.2. DM picture

In the DM model, the DM in the formation epoch may have determined the star formation efficiency (Hirashita et al. 1998) and also the present physical state of the galaxy. Assuming that the masses of the dSphs are dominated by the DM, the tidal forces could have no effect on the dSphs because their tidal radii are larger than their core radii (Pryor 1996). Since there is no reason why more extended dSphs are closer to the Galaxy or M31 in the DM model, it seems rather natural that no significant correlation between $R_{\rm GC}$ and C is found. In other words, the physical conditions of the dSphs should be determined by their DM contents, not by their environments. Thus, the DM model does not break down even in front of our result.

4.2.3. Possible heterogeneity of the dSph sample

It should be noted that the group of so-called dSph satellites may be heterogeneous. Some may well be evolved "normal" low-mass galaxies in the sense that they contain dark matter and have a cosmological origin, and some may be secondary satellites that formed during mergers of gas-rich protogalactic clumps contain little DM and have a globular cluster-like origin. The latter of these systems will not contain dark matter, and will be significantly affected by tides while orbiting around the larger parent galaxy. Moreover, remnants of these can be long-lived and may fake domination by DM (Kroupa 1997, Klessen & Kroupa 1998). Therefore, it is worthwhile examining whether our result make some

difficulties in accepting such heterogeneity. In Figure 2, all the Milky Way satellites except for Sculpter, have positive values of C, and in addition, their $\log R_{GC}$ and C seems to correlate. Note that Sagittarius is believed to be experiencing serious tidal modification. Thus it may be true that among the satellites of the Galaxy in our sample, only Sculpter is exceptionally a DM dominated dSph, and the tidal effects are the dominating factor for the others. However, since there is no clear evidence of the heterogeneity, all we can do here is to mention it as one possibility.

5. Summary

In order to investigate the tidal effect on the Local Group dSphs, we examined the correlation between the distances from their host galaxy (the Galaxy or M31) and the compactnesses of their surface brightness profiles, "C" defined newly in this paper for the dSphs. As a result, we find no significant correlation and thus no direct evidence that tidal effects have a major effect on the dSphs. However, in most cases, C is sufficiently large to allow the possibility of tidal effects, especially so since C decreases for the furthest dSph satellites of the Galaxy. Based on this result, we discussed the validity of the existing pictures which have been suggested to explain fundamental properties, especially the origin of their large mass-to-luminosity ratios, of the dSphs.

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Figure Caption

Fig. 1— The relation between the core radius (r_c) and V band absolute magnitude (M_V) for the sample dSphs is shown. Filled squares indicate the dSphs which are companions of the Galaxy and open squares indicate those of M31. The solid line indicates the relation that we use to derive the standard core radius for each dSph (see text for detail). The area marked with dEs represents a typical locus of dwarf elliptical galaxies (e.g., Peterson & Caldwell 1993).

Fig. 2— Log $R_{\rm GC} - C$ relation (see text for their detailed definitions) of our sample dSphs. Filled squares and open squares have the same meanings as those in Fig. 1.

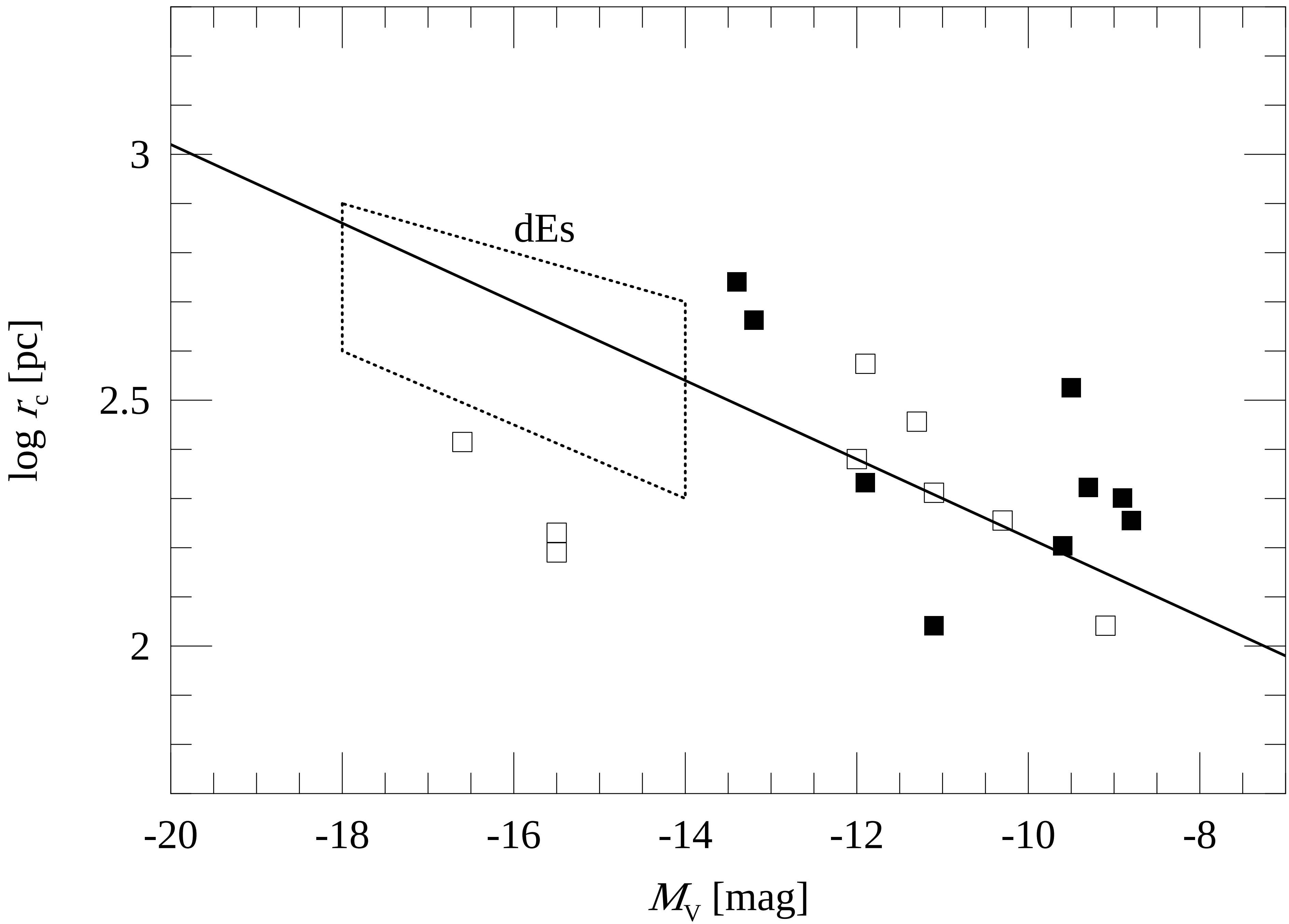
Table 1: Parameters of the Local Group dwarf spheroidal galaxies

Galaxy Name	M_V (mag)	r_c (pc)	$R_{\rm GC}$[a] (kpc)	C[b]	Parent Galaxy
Sagittarius	−13.4	550[c]	16±2	0.28	
Draco	−8.8	180±43	76±6	0.16±0.09	
Carina	−9.3	210±29	89±5	0.19±0.05	
Ursa Minor	−8.9	200±15	66±3	0.20±0.03	
Sextans	−9.5	335±24	91±4	0.38±0.03	the Galaxy
Sculptor	−11.1	110±30	78±4	−0.24±0.10	
Fornax	−13.2	460±27	133±8	0.22±0.02	
Leo I	−11.9	215±20	270±30	−0.01±0.04	
Leo II	−9.6	160±33	219±12	0.05±0.08	
NGC 147	−15.5	170[c]	109±22	−0.40	
NGC 185	−15.5	155±47	178±21	−0.44±0.12	
NGC 205	−16.6	260±5	45±35	−0.30±0.01	
And I	−11.9	375±19	57±30	0.23±0.02	
And II	−11.1	205±10	281±88	0.03±0.02	M31
And III	−10.3	180±24	67±16	0.04±0.05	
And V	−9.1	110±5	115±23	−0.08±0.02	
And VI	−11.3	286±7	280±85	0.16±0.01	
And VII	−12.0	240±6	215±75	0.03±0.01	

[a]This value means the Galactocentric distance from each galaxy for the Galaxy's companion, and the distance from M31 for M31's companion.

[b]C represents "compactness parameter" (see text in detail).

[c]Error bars of r_c are not attached to in the literatures.


log r_c [pc]
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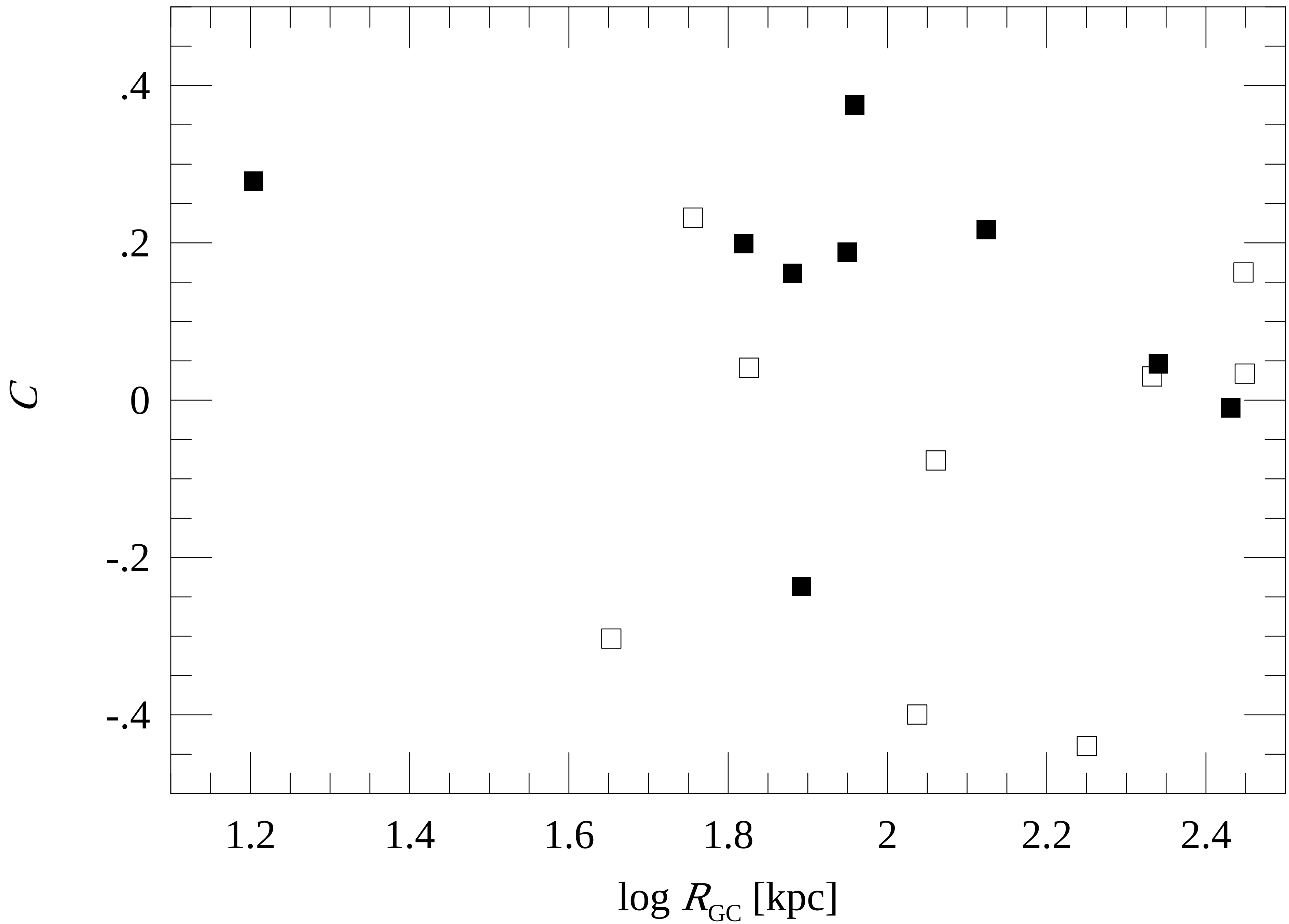
2.5
2
dEs
-20
-18
-16
-14
-12
-10
-8
M_V [mag]



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